University of Basel

Probing New Physics with Flavor Tagging at FCC-ee

Based on Greljo, Tiblom, Valenti; [2411.02485]

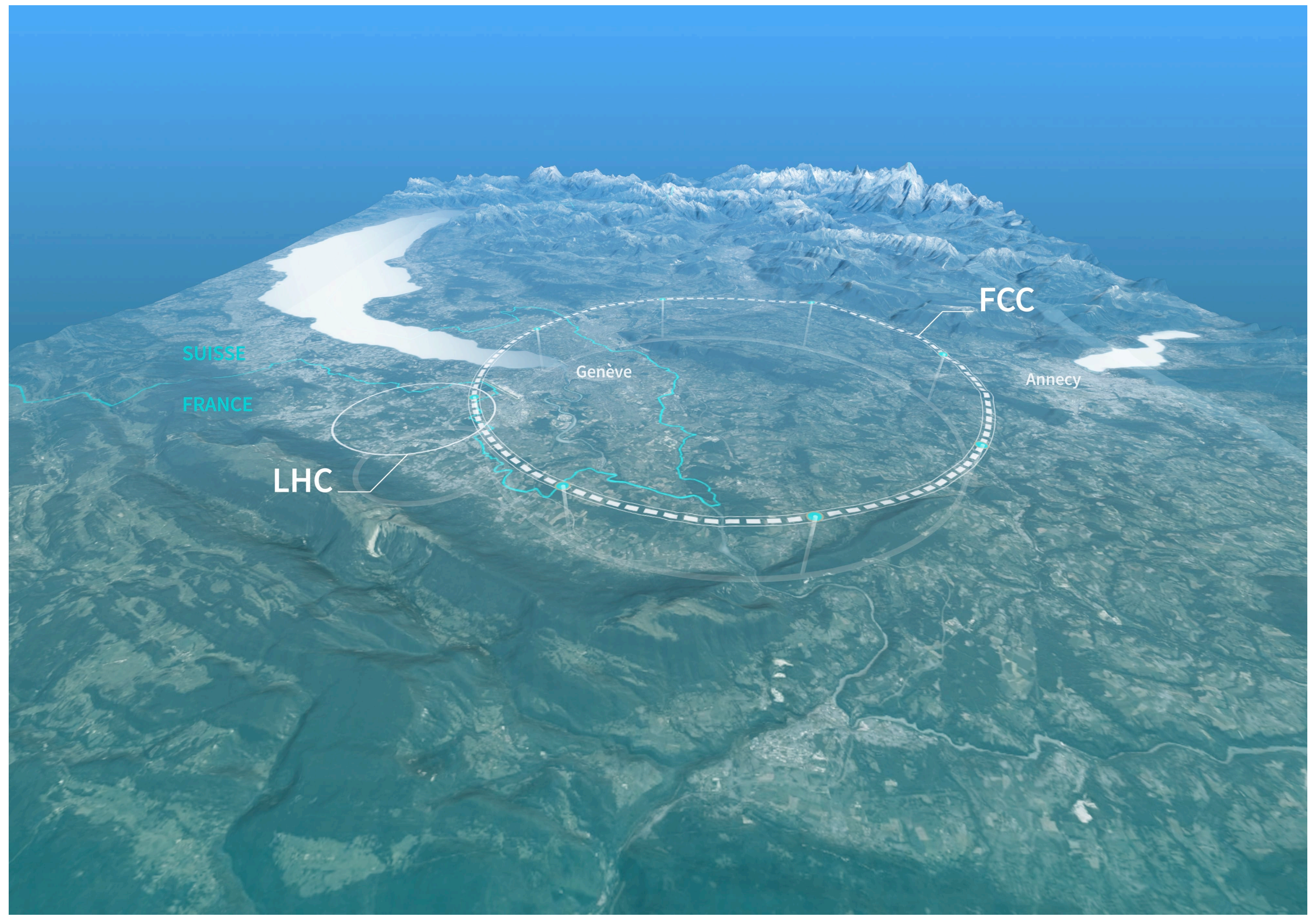
Hector Tiblom - PLANCK2025 - May 28, 2025

FCC-ee plan

Four key stages

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics Goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^{8} WW	10^{6} HZ + 25k WW $\rightarrow$ H	$10^{6}\,t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H	

Blondel, Janot; [2106.13885]



Source: CERN

Previous analyses

Z, *W*-pole expected to probe new physics up to $\mathcal{O}(10-100)$ TeV

Observable	Value	Error	FCC-ee Tot.
Γ_W [MeV]	2085	42	1.24
m_W [MeV]	80350	15	0.39
$\mathrm{Br}(W \to e\nu)(\%)$	10.71	0.16	0.0032
$\mathrm{Br}(W \to \mu\nu)(\%)$	10.63	0.15	0.0032
$\mathrm{Br}(W \to \tau\nu)(\%)$	11.38	0.21	0.0046
$\tau \to \mu\nu\nu(\%)$	17.39	0.04	0.003
$\tau \to e\nu\nu(\%)$	17.82	0.04	0.003

Current and projected errors for *W*-pole and τ observables, adapted from Allwicher, Cornella, Isidori, Stefanek; [2311.00020]

Observable	Curr. Rel. Err. (10^{-3})	FCC-ee Rel. Err. (10^{-3})
Γ_Z	2.3	0.1
σ^0_{had}	37	5
R^Z_b	3.06	0.3
R^Z_c	17.4	1.5
$A^{0,b}_{\mathrm{FB}}$	15.5	1
$A^{0,c}_{\mathrm{FB}}$	47.5	3.08
A^Z_b	21.4	3
A^Z_c	40.4	8
R^Z_e	2.41	0.3
R^Z_μ	1.59	0.05
R^Z_τ	2.17	0.1
$A^{0,e}_{\mathrm{FB}}$	154	5
$A^{0,\mu}_{\mathrm{FB}}$	80.1	3
$A^{0,\tau}_{\mathrm{FB}}$	104.8	5
A^Z_e	14.3	0.11
A^Z_μ	102	0.15
A^Z_τ	102	0.3
N_ν	50	0.8

Current and projected errors for *Z*-pole observables, adapted from Allwicher, Cornella, Isidori, Stefanek; [2311.00020]

This talk

- Our focus: $e^+e^- \to f\bar{f}$ observables *above* the Z-pole
- Interpret using dim-6 SMEFT 4F operators
- FCC-ee impact on a specific NP model

More events ↑

WW

$\sqrt{s} = 163\,\mathrm{GeV},\ \mathcal{L} = 10\,\mathrm{ab}^{-1}$

ZH

$\sqrt{s} = 240\,\mathrm{GeV},\ \mathcal{L} = 5\,\mathrm{ab}^{-1}$

$t\bar{t}$

$\sqrt{s} = 365\,\mathrm{GeV},\ \mathcal{L} = 1.5\,\mathrm{ab}^{-1}$

More energy ↓

Four fermion observables

$$R_b = \frac{\sigma(e^+e^- \to b\bar{b})}{\sum_{q=u,d,s,c,b} \sigma(e^+e^- \to q\bar{q})}$$ equiv. for s, c

prob. of tagging z as i

Mean number of events per bin: $$N_{ij} = N_{\text{tot}} \sum_z \frac{2}{1+\delta_{ij}} R_z \epsilon_z^i \epsilon_z^j$$

Fit params. R_z, N_{tot}, ϵ_i^i ⟵ true positive rates

$$-2\log L = \sum_{ij} \frac{(N_{ij}^{\text{exp}} - N_{ij})^2}{N_{ij}^{\text{exp}}} + \frac{x_{ij}^2}{(\delta_\epsilon)^2}$$

nuisance param. for ϵ_i^j

syst. uncertainty

Case study: R_b

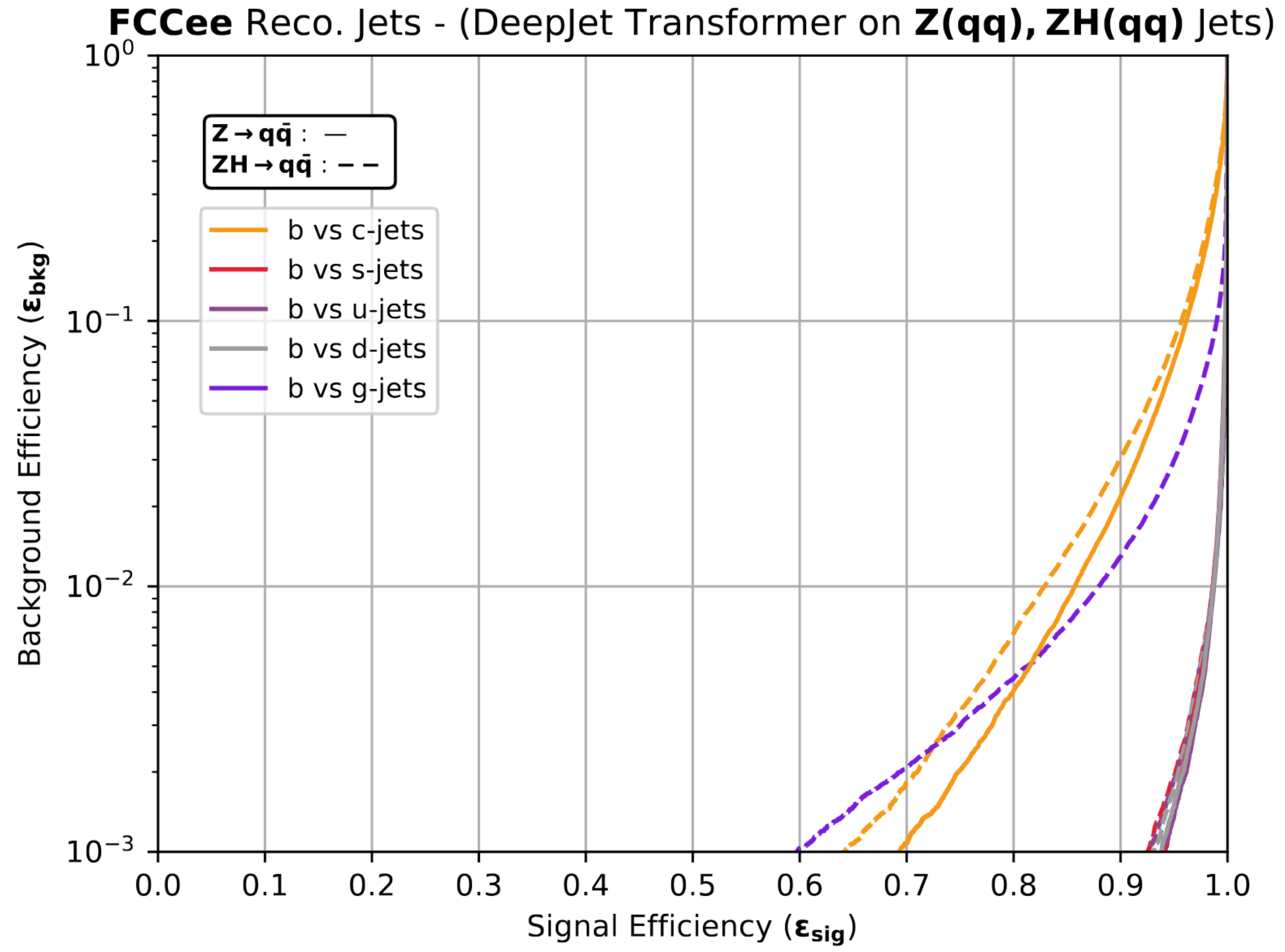
- Only two flavors b, j

$$N(n_b = 2) \equiv N_2 = N_{\rm tot}[(\epsilon_b^b)^2 R_b + (\epsilon_j^b)^2 R_j]\,,$$
$$N(n_b = 1) \equiv N_1 = 2N_{\rm tot}[\epsilon_b^b(1-\epsilon_b^b)R_b + \epsilon_j^b(1-\epsilon_j^b)R_j]\,,$$
$$N(n_b = 0) \equiv N_0 = N_{\rm tot}[(1-\epsilon_b^b)^2 R_b + (1-\epsilon_j^b)^2 R_j]$$

- FCC-ee ROC curves from *DeepJetTransformer*

- Take $\delta_\epsilon \simeq 0.01$, consider *WW* run

- $\Delta R_b / R_b \simeq 2 \cdot 10^{-4}$ (almost naive stat. limit $1/\sqrt{N_{\rm tot} R_b}$)



Bottom tagging (Blekman, Canelli et al; [2406.08590])

LEP-II: $\Delta R_b / R_b \sim 10^{-2}$
LEP EW WG [1302.3415]

$$\left(\frac{\Delta R_b}{R_b}\right)^2 = \underbrace{\frac{1-\epsilon_b^b(2-\epsilon_b^b(2-R_b))}{N_{\rm tot}R_b(\epsilon_b^b)^2}}_{\text{True positive statistical error}} + \underbrace{\frac{2(\epsilon_b^b - R_b(2-\epsilon_b^b)(2\epsilon_b^b-1))}{N_{\rm tot}R_b^2(\epsilon_b^b)^3}\epsilon_j^b}_{\text{False positive statistical error}} + \underbrace{\frac{4(R_b-1)^2(\epsilon_j^b)^2}{R_b^2(\epsilon_b^b)^2}(\delta_\epsilon)^2}_{\text{False positive systematic error}} + \mathcal{O}\left((\epsilon_j^b)^2\right)$$

Full fit

- We extend our fit to consider R_a, R_t, R_ℓ simultaneously

- Small correlations between R_a, for *WW*:

$$\rho = \begin{pmatrix} 1 & -0.006 & -0.22 \\ -0.006 & 1 & -0.006 \\ -0.22 & -0.006 & 1 \end{pmatrix}$$

$\mathcal{O}(10^2)$ improvement over LEP-II!

Observable/FCC-ee Rel. Err. (10^{-3})	WW	Zh	$t\bar{t}$
R_b	0.17	0.36	0.96
R_s	3.7	5.8	10
R_c	0.14	0.27	0.69
R_t	-	-	1.2
$R_{\tau,\mu}$	0.16	0.35	0.97
R_e	0.50	0.52	0.64

Projected errors for our beyond the *Z*-pole observables

s-tagging has room for improvement

R_t, R_μ, R_τ statistically limited

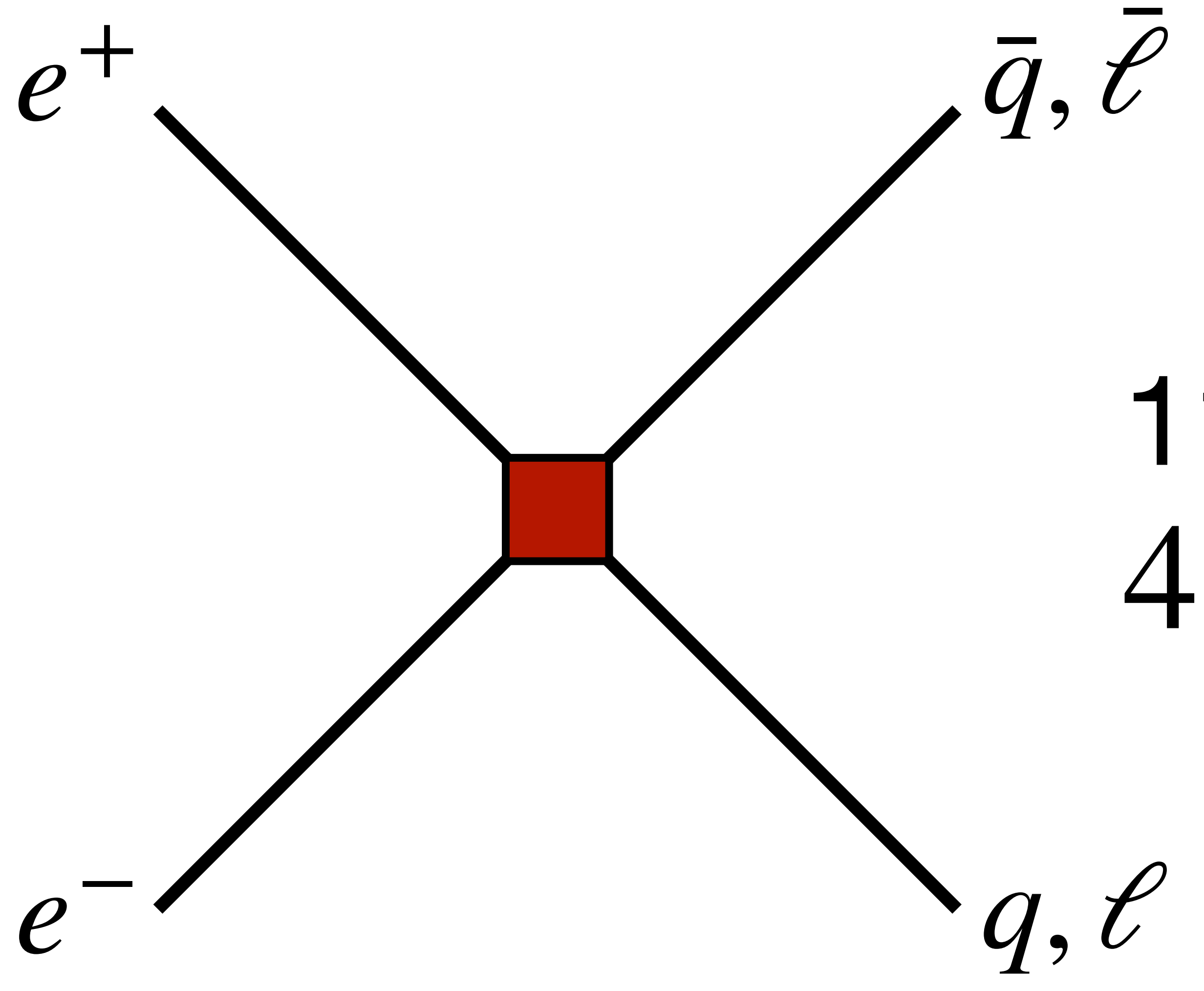
R_e limited by systematics

SMEFT interpretation

- Extend SM with higher-dimensional operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$$

- Set $c_i = 1$, turn on one at a time, gives lower bound on Λ_i

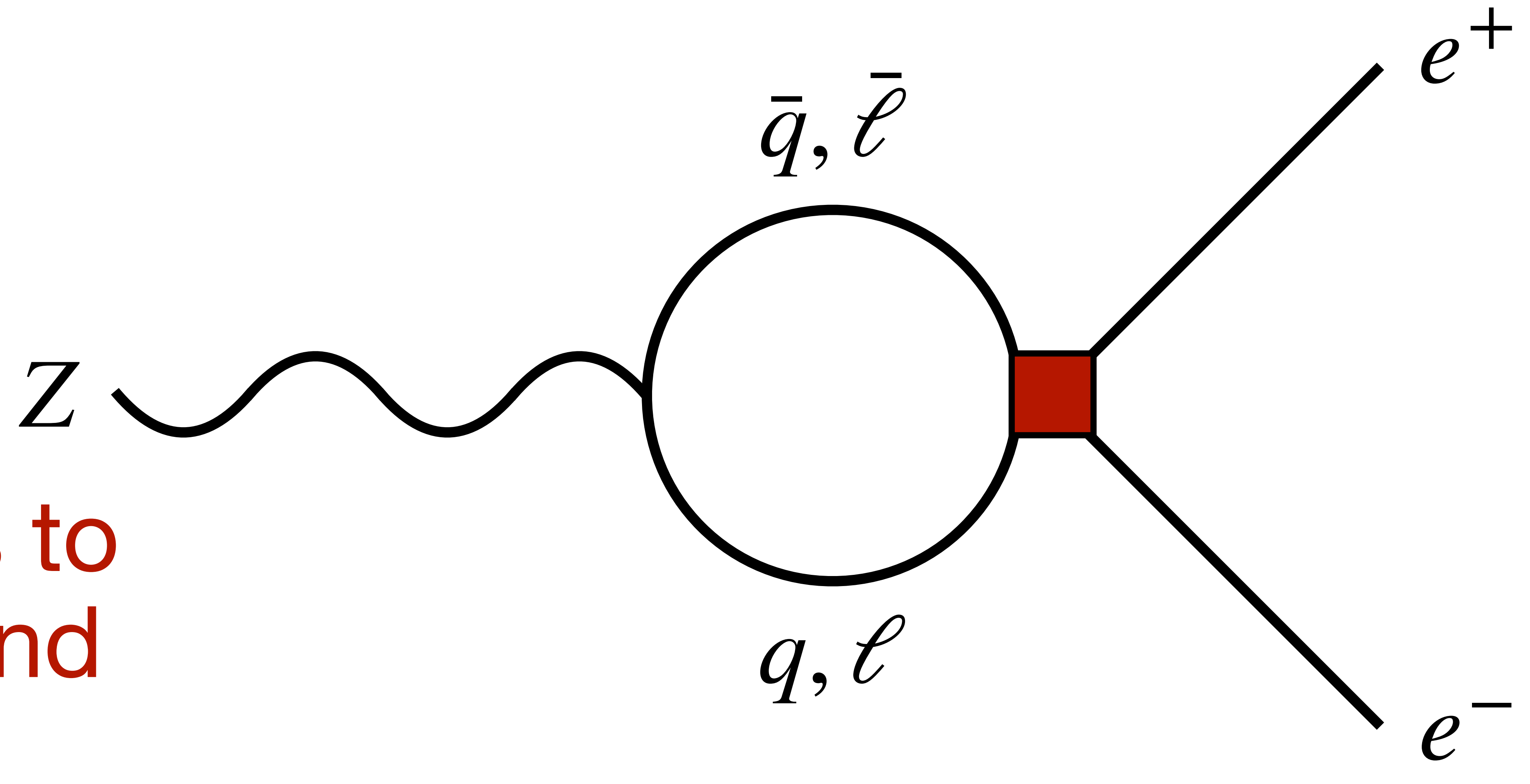


11xx $2q2\ell$ & 4ℓ operators

- Increasing *s*: lower precision on R_a, R_ℓ
- But error scales with energy $\Delta R_a / R_a \sim s/\Lambda^2$

$$\Lambda_{qe,3311} = \{\underset{WW}{17.8}, \underset{ZH}{17.4}, \underset{t\bar{t}}{16.5}\}\ \text{TeV}$$

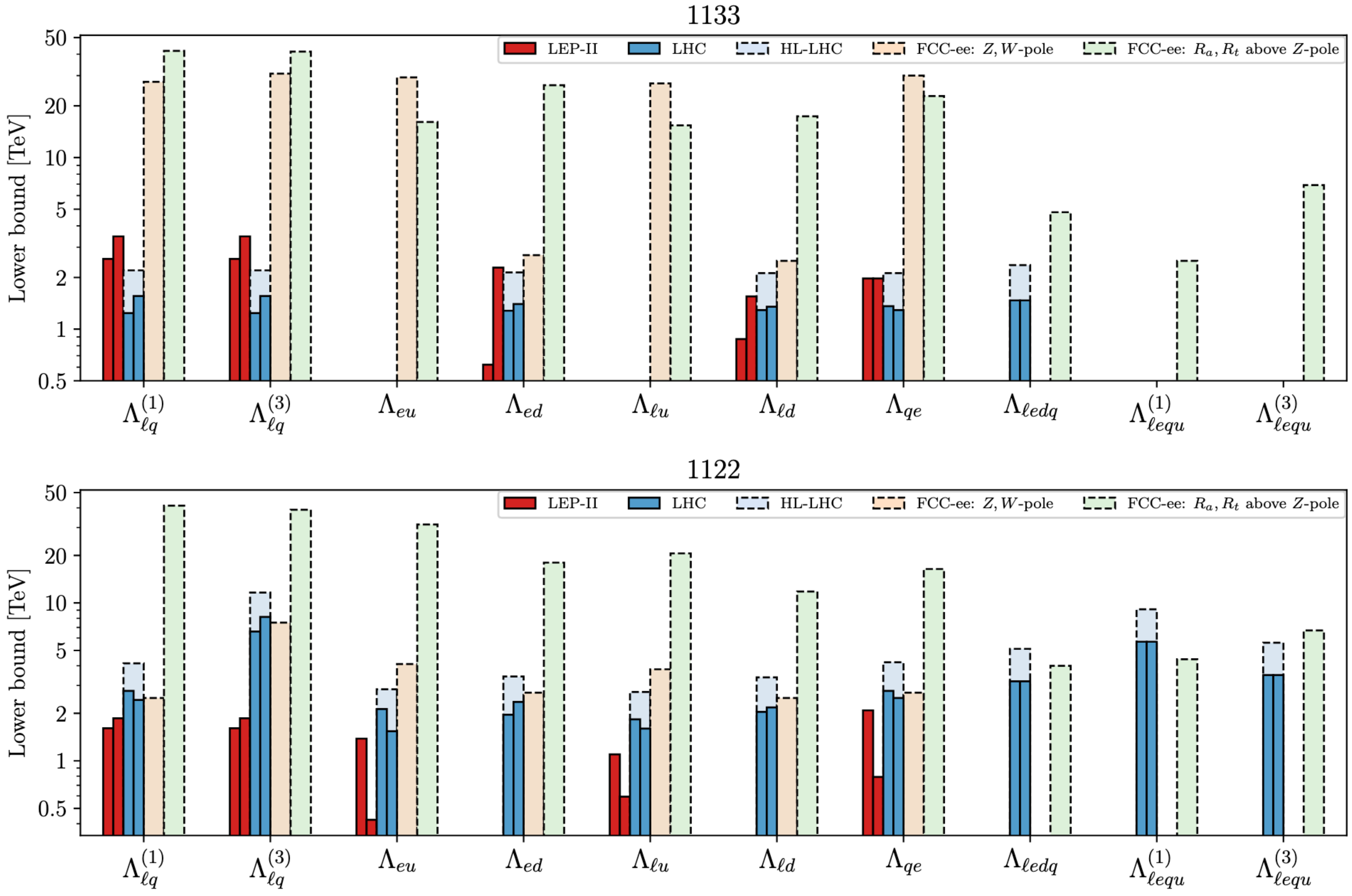
Combine runs to get lower bound at 95% CL



Semileptonic

- LEP-II bounds from R_a ratios
- LHC & HL-LHC bounds from high-p_T Drell-Yan
- FCC-ee Z-pole bounds from one-loop RGE ($\propto y_t^2$ or gauge)

FCC-ee will improve by an order of magnitude!

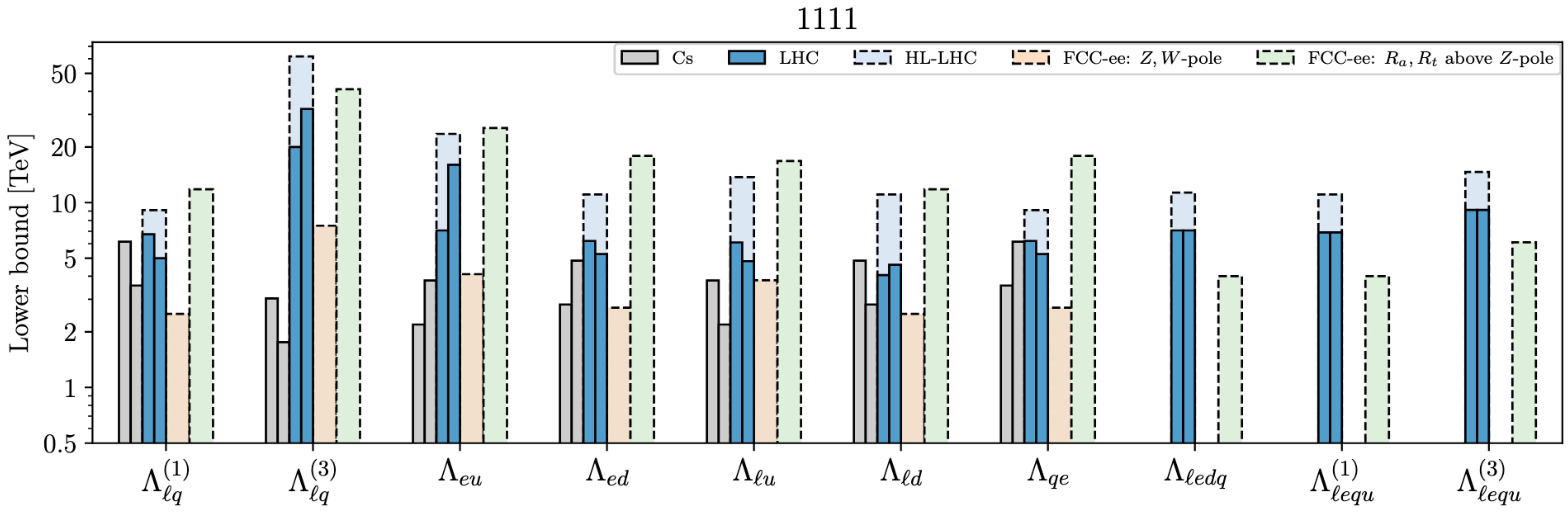


Tree-level bounds for the semileptonic operators (95% CL)

Semileptonic

- Cs bounds from atomic parity violation
- LHC & HL-LHC bounds from high-p_T Drell-Yan
- FCC-ee Z-pole bounds from one-loop RGE ($\propto y_t^2$ or gauge)

FCC-ee will only provide comparable bounds to HL-LHC above the Z-pole



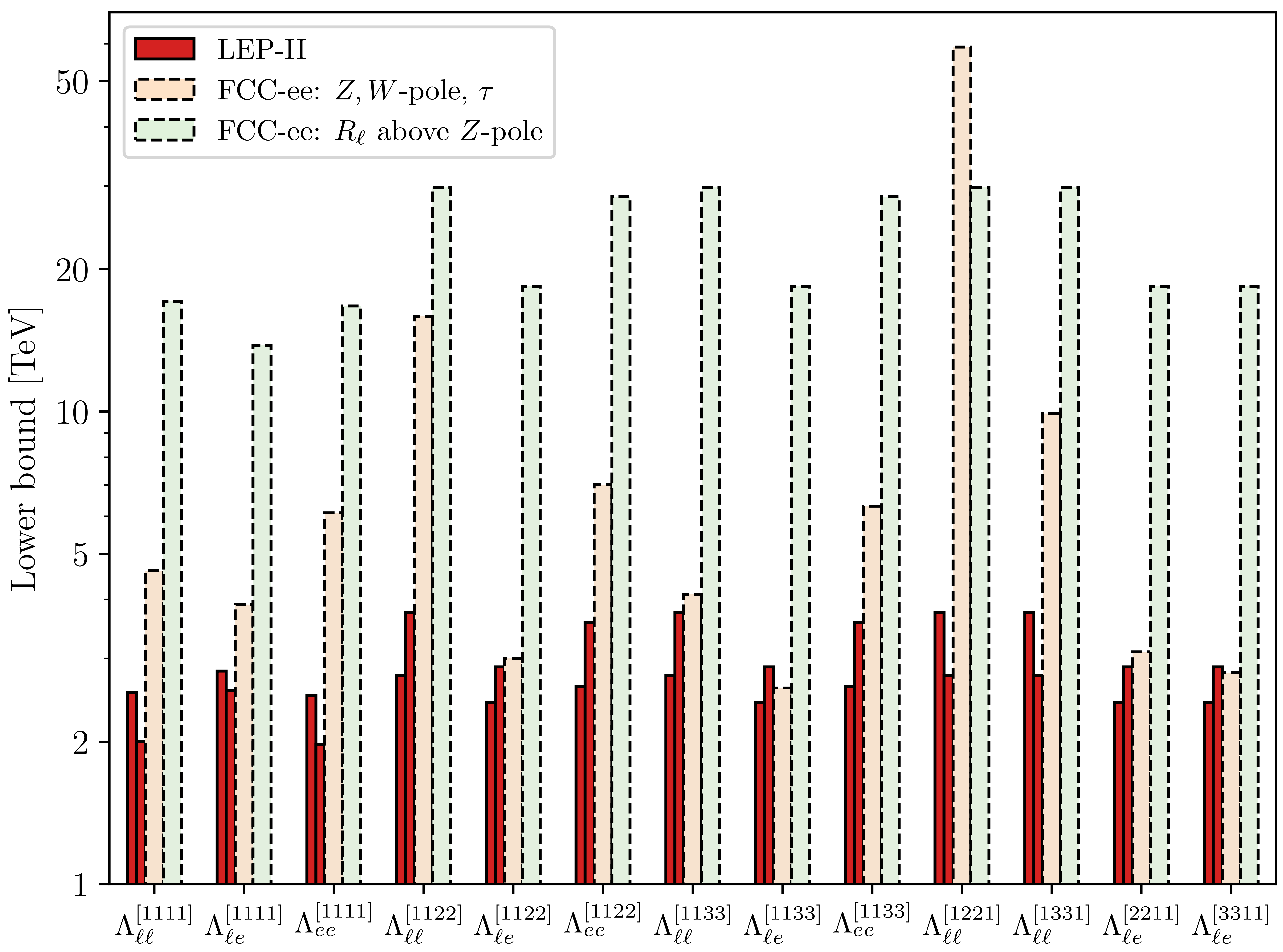
Tree-level bounds for the semileptonic operators (95% CL)

Fully leptonic

- LEP-II bounds from R_ℓ ratios
- FCC-ee Z-pole bounds from one-loop RGE ($\propto y_t^2$ or gauge)

FCC-ee will improve by an order of magnitude!

Extra strong bounds for $\Lambda_{\ell\ell}^{[1221]}$ because it contributes to G_F at tree-level through muon decay



Tree-level bounds for the fully leptonic operators (95% CL)

Production asymmetries

- Forward-backward asymmetry complements leptonic ratios

$$A_\ell = \frac{\sigma_F(e^+e^- \to \ell^+\ell^-) - \sigma_B(e^+e^- \to \ell^+\ell^-)}{\sigma_F(e^+e^- \to \ell^+\ell^-) + \sigma_B(e^+e^- \to \ell^+\ell^-)}$$

- Assuming only stat. error $\Delta A_\ell / A_\ell = \{3.3, 8.8, 27\} \times 10^{-4}$ LEP-II: $\Delta A_\ell / A_\ell \sim 10^{-2}$

$WW \quad ZH \quad t\bar{t}$

- Exp. study needed to determine the validity of this assumption

Observable/Λ [TeV]	$\Lambda_{\ell\ell,11xx}(\Lambda_{\ell\ell,1xx1})$	$\Lambda_{\ell e,11xx}(\Lambda_{\ell e,xx11})$	$\Lambda_{ee,11xx}$
R_ℓ	29.8	18.4	28.5
A_ℓ	11.7	18.1	11.2

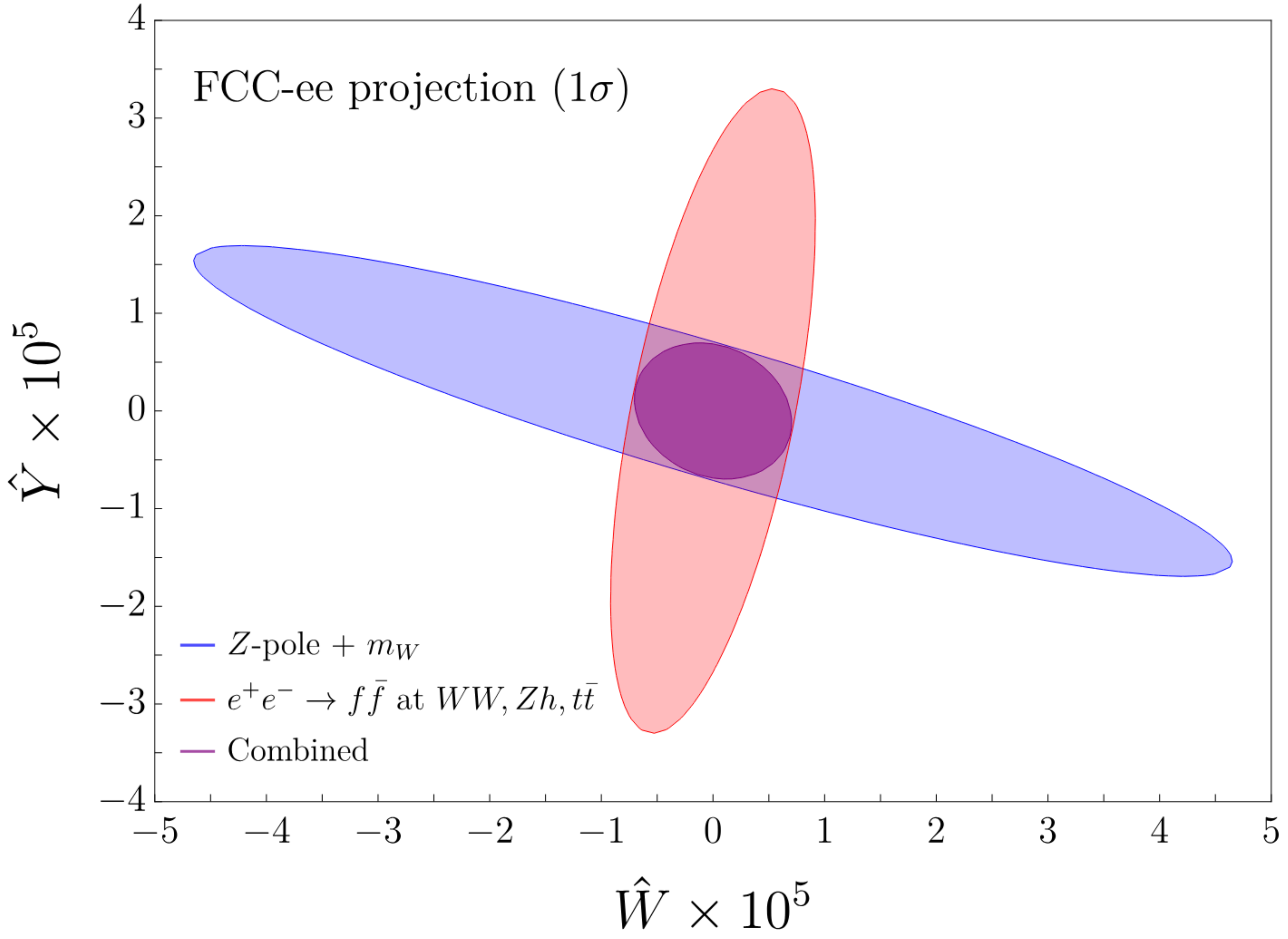
$x = 2,3$

Oblique corrections

$$\mathcal{L}_{\text{SMEFT}} \supset -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

- *Z, W*-pole observables: Higgs-fermion current operators at TL
- R_a, R_ℓ above the pole: flavor-conserving universal 4F operators at TL

	$\hat{W} \times 10^5$	$\hat{Y} \times 10^5$
Current (LHC)	$[-19, 5]$	$[-31, 14]$
HL-LHC	$[-4.5, 6.9]$	$[-6.4, 8.0]$
FCC-ee pole observables	$[-3.1, 3.1]$	$[-1.1, 1.1]$
FCC-ee above the pole	$[-0.60, 0.60]$	$[-2.2, 2.2]$



Z' model

- Consider a model with $Z'_\mu \sim (\mathbf{1}, \mathbf{1}, 0)$

  $$\mathcal{L} \supset g_{ij}\bar{q}_i\gamma_\mu q_j Z'^\mu + g_\ell(\bar{\ell}_\alpha\gamma_\mu\ell_\alpha + \bar{e}_\alpha\gamma_\mu e_\alpha)Z'^\mu$$

- $b \to s\ell\ell$ anomalies ⟶ bound on $r_\ell r_{sb}$
- B_s mixing ⟶ bound on r_{sb}
- R_b at LEP-II ⟶ bound on r_ℓ

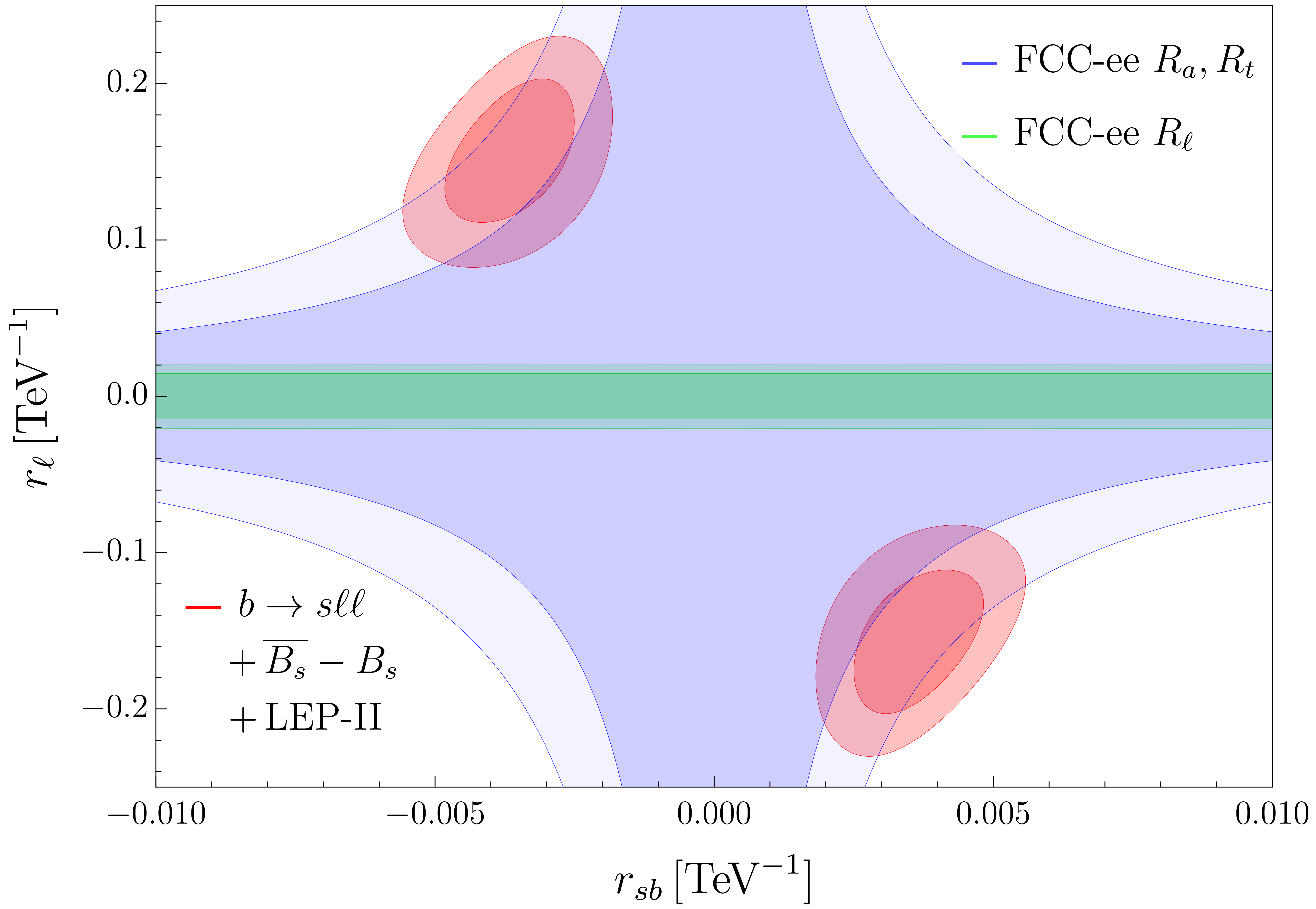
$r_{sb} = g_{sb}/M$

$r_\ell = g_\ell/M$

(M: Z' mass)

Z' results

- Hadronic ratios at FCC-ee: partial probe of parameter space
- Leptonic ratios at FCC-ee: complete probe of parameter space



Darker and lighter shades indicate 1σ and 2σ respectively

Conclusions

- FCC-ee can deliver $\mathcal{O}(10^2)$ improvement of LEP-II results for R_a, R_ℓ
- Hadronic ratios above the *Z*-pole at FCC-ee will probe non-universal 4F operators up to $\mathcal{O}(40)$ TeV!
- R_a, R_ℓ at TL provides complementary results to 1-loop results for *Z, W*-pole EWPO
- For the considered *Z'* model, FCC-ee can exclude it definitely

Thank you for your attention!

Backup slides

RG effects

- At one-loop, four-quark operators will contribute, as well as semileptonic and leptonic operators with indices other than 11xx
- We focus on the indices = 3333 which are currently the least constrained operators

$\Lambda^{[3333]}$ [TeV]	FCC-ee Z, W-pole+τ	FCC-ee above Z-pole
$\Lambda_{\ell q}^{(1)}$	15.7	1.1
$\Lambda_{\ell q}^{(3)}$	14.0	5.1
Λ_{eu}	16.2	1.6
Λ_{ed}	1.5	1.3
$\Lambda_{\ell u}$	15.4	1.5
$\Lambda_{\ell d}$	1.5	1.3
Λ_{qe}	16.7	1.1
$\Lambda_{\ell\ell}$	1.0	1.0
$\Lambda_{\ell e}$	2.1	1.5
Λ_{ee}	3.5	2.4
$\Lambda_{qq}^{(1)}$	13.1	2.4
$\Lambda_{qq}^{(3)}$	8.4	7.1
$\Lambda_{qu}^{(1)}$	9.4	1.4
$\Lambda_{qd}^{(1)}$	3.1	0.9
Λ_{uu}	12.1	1.9
Λ_{dd}	0.4	2.3
$\Lambda_{ud}^{(1)}$	2.8	1.9

One-loop bounds at and above the Z-pole (95% CL)

Flavor violating

- Now consider $e^+e^- \to q_i\bar{q}_j$
- Focus only on N_{ij} bin
- Only competitive bounds for SMEFT operators with a RH up-type quark
- Meson decays provide superior bounds for *bs* and *bd*

$$|\Lambda_{1123}| > 16\,\text{TeV} \;\text{ for }\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe}$$

$$|\Lambda_{1113}| > 9.4\,\text{TeV} \;\text{ for }\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell d}, \mathcal{O}_{ed}, \mathcal{O}_{qe}$$

$$|\Lambda_{1112}| > 8.1\,\text{TeV} \;\text{ for }\; \mathcal{O}_{\ell q}^{(1)}, \mathcal{O}_{\ell q}^{(3)}, \mathcal{O}_{\ell u}, \mathcal{O}_{eu}, \mathcal{O}_{qe}$$

Bounds on FV 4F SMEFT operators at 95% CL

Energy	ij	R_{ij}
WW	bs	$2.80 \cdot 10^{-6}$
	bd	$3.44 \cdot 10^{-5}$
	cu	$5.28 \cdot 10^{-5}$
Zh	bs	$6.37 \cdot 10^{-6}$
	bd	$6.58 \cdot 10^{-5}$
	cu	$1.10 \cdot 10^{-4}$
$t\bar{t}$	bs	$1.79 \cdot 10^{-5}$
	bd	$1.53 \cdot 10^{-4}$
	cu	$2.70 \cdot 10^{-4}$

Bounds on the FV hadronic ratios at 95% CL